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Automatic Barometric Updates from Ground-Based Navigational Aids

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16. Abstract

This study examined techniques for transmitting automatic barometric updates of altimeter settings to pilots from ground-based navigation aids. It also examined the human factors and operational impact of providing automatic altimeter updates to flight crewmembers. The study considered the altimeter setting procedures of general aviation aircraft pilots operating in compliance with the Visual Flight Rules. And, it considered the altimeter setting procedures of pilots operating within the Instrument Flight Rules requirements. The study concludes that there are no insurmountable human factors or operational problems associated with the implementation of ABU, if the technique is based on automatic transmission of the barometric data through synthesized or digitized voice updates from the selected navigation aids. The study also concluded there is potential for improvement of aviation safety by implementing ABU techniques. These improvements would be in the form of: 1) enhancement of the quality of altimeter setting data used by VFR flight crewmembers operating below 18,000 feet MSL, 2) a reduction of workload for flight crewmembers operating in either VFR or IFR environments, 3) a reduction of air traffic controller workload, and, 4) a small, but positive, reduction of traffic on ATC communication channels.

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Executive Summary

This study examined techniques for transmitting automatic barometric updates of altimeter settings to pilots from ground-based navigation aids. It also examined the human factors and operational impact of providing automatic altimeter updates to flight crewmembers.

Because the maintenance of accurate aircraft operating altitude is of paramount importance to the control of air traffic, accountability and/or compensation for non-standard atmospheric pressure distribution is rigorously practiced. Altimeter-setting procedures are routinely accomplished to minimize effects of barometric pressure variations in flight. Since procedures often rely heavily on "live" altimeter setting data transmissions between controllers and pilots, their use impacts the human operator in the form of workload for both. This is especially the case for ATC scenarios involving aircraft descents and transitions from jet route structures to the approach and landing environments. High levels of air traffic and communication traffic elevates the workload and reduces the time available to accomplish required tasks. Other altimeter setting issues involve the apparent limited availability of appropriate altimeter setting data for VFR operators.

Techniques for automatic barometric update (ABU) transmissions of altimeter settings to pilots from ground-based navigation aids have been examined for suitability in relieving (IFR) pilot and controller workloads and for improving the accessibility of appropriate barometric update data to VFR operators.

Also examined are the human factors impact and operational risks associated with implementing ABU system concepts into the NAS.

The study concludes that there are no insurmountable human factors or operational problems associated with the implementation of ABU, if the technique is based on automatic transmission of the barometric information through synthesized or digitized <u>voice</u> updates from the selected navigation aids.

The study also concluded there is potential for improvement of aviation safety by implementing ABU techniques. These improvements could be in the form of: 1) enhancement of the quality of altimeter setting data used by VFR flight crewmembers operating below 18,000 feet MSL, 2) a reduction of workload for flight crewmembers operating in either VFR or IFR environments, 3) a reduction of air traffic controller workload, and, 4) a small, but positive, reduction of traffic on ATC communication channels.

JPM1. This would be a good place to insert a Glossery of Acronyms. All Acronyns used in this document should be defined in one place.

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1.0 INTRODUCTION

1.1 Background

The accuracy of barometric flight altimeters is affected by a number of factors, not the least of which is a non-uniform, constantly-changing, atmospheric pressure distribution. And, since weather systems are characterized by varying pressure gradients as well as varying speeds of movement, the lack of pressure uniformity may also be accompanied by wide variations in the rate of barometric pressure change for any specific atmospheric position. Furthermore, the rate of change of barometric pressure, as it affects flight altitude measurements, is also modified by the speed and flight direction of aircraft operating within any specific airmass or weather system. Other altimeter errors include installation error, temperature error, and hysteresis error. However, the error which this study is primarily concerned is the error introduced by exposure to a constantly-changing barometric pressure.

The maintenance of accurate aircraft operating altitude is a one of the principal factors upon which aircraft traffic separation is based. Because of its importance in maintaining traffic separation within the National Airspace System (NAS), errors caused by variations of the atmospheric pressure must be rigorously and continuously accounted for. Flight crewmembers operating aircraft within the defined Jet Route System--jet routes from 18,000 feet Mean Sea Level (MSL) to Flight Level FL450--account for variations in atmospheric pressure distribution by setting their altimeters to the sea level standard of 29.92 (inches of mercury). Therefore, all aircraft operating within the Jet Route System are affected similarly to pressure variations at any specific point in the system. However, flight crewmembers operating below 18,000 feet MSL (or below the lowest usable Flight Level) must frequently update their altimeters to compensate for barometric pressure variations.

1.2 Need For Enhanced ATC Procedures

Procedures for correcting or updating the altimeter to minimize altitude errors have been in routine use for many years; their development being dictated by the technology and air traffic control systems in use at the time. While these procedures have served well, past and projected increases in air traffic and their impact on air traffic controller and flight crewmember workloads (as well as its impact on communication systems) suggests that an examination of these procedures for potential enhancement may be timely and appropriate. This examination may also be warranted, considering the capabilities of the communication and navigation (COMNAV) systems currently in routine service within the National Airspace System (NAS).

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A review of options for developing enhanced capabilities and procedures, based on the use of current NAS systems and other state-of-the-art technology, is needed to determine if altimeter setting information can be provided more efficiently for pilots operating below the jet route structures.

A review of current altimeter setting procedures may also be particularly worthwhile in view of the reduced number of Flight Service Station (FSS) facilities being maintained by the Federal Aviation Administration (FAA). If the trend toward fewer FSSs continues, the number of facilities where current altimeter settings may be obtained could be reduced even further. In this case, the development of alternate sources for barometric updates may eventually become a priority effort for the FAA to provide easy and timely access to continuously-changing altimeter setting information.

Furthermore, this may be of particular interest and benefit to the segment of the flying public who are operating in compliance with the Visual Flight Rules (VFR). Without the ability of this group to consistently secure appropriate altimeter settings for localized conditions, there is a possibility that some of their aircraft could be operating within the NAS at other than optimum altitudes.

Aside from this concern, there is also concern that current Instrument Flight Rules (IFR) procedures requiring Air Traffic Control (ATC) controllers to issue altimeter settings tend to elevate operator workload--both pilot and controller. If, through a form of automation of barometric updates, altimeters can be set without the need for voice communications between pilots and ATC, a small, but beneficial, relief in pilot and controller workloads may result. Furthermore, if this can be done, other benefits may also be found through a reduction of the communication traffic on congested ATC radio frequencies.

Considering the projected growth in air traffic, a review of possible techniques to provide relief for these concerns appears to be a most appropriate initiative.

2.0 OBJECTIVES AND APPROACH

2.1 Project Objectives

The primary objectives of this study are to determine if there are technologies and viable concepts for automating the task of setting the barometric pressure reference for altimeters of aircraft flying below 18,000 feet MSL.

These objectives include an examination of potential benefits to be derived by an Automatic Barometric Update (ABU) system that would:

- Reduce flight altitude errors of aircraft operating within the NAS through timely updating of barometric flight altimeters.

- Provide simplification of flight operational procedures through combinations of automation and timely updating of barometric altimeters.

- Provide potential for reductions in controller and pilot workload.

- Support increased safety of flight operations within congested geographical areas.

- Provide potential for improved accuracy of the vertical separation of traffic enroute along the nation's air corridors.

2.2 Approach

The approach to be taken to evaluate viable concepts for automatic updating of flight altimeters will be conducted in two phases.

Phase I: Study of Concept Options vs. Procedure Enhancement.

Phase II: Initial Laboratory/Desktop Demonstration and Definition of Candidate Proof-of-Concept ABU System Requirements.

The first phase will involve the development of concept options along with an evaluation of the potential for these options to provide timely, accurate altimeter updates and, at the same time, provide enhancement to controller and pilot procedures without introducing negative human factors on the personnel involved.

Phase I includes:

A review of the IFR and VFR procedures currently in use for updating barometric altimeters; a study of the technical and operational merits of providing automated barometric altimeter updates or altimeter settings through transmissions or broadcasts from VHF omni-directional ranges (VORs), tactical air navigation systems (TACANs), non-directional beacons (NDBs), and other types of ground-based navigational aids such as the Instrument Landing System (ILS).

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A discussion of the accuracy and reliability requirements for
sensors and transmission functions necessary for an ABU
system, including a preliminary evaluation of the operational
and human factors impacts associated with information being
transmitted to the aircraft as a shared-signal communication
feature within the navigation facilities' service volume.

This evaluation is accomplished through an examination of various
human interface situations within the NAS system. It uses ATC
and flight operational scenarios to assure that adequate
situational awareness is maintained where automated altimeter
update functions are applied to controller or pilot procedures.

Using the concept options developed in Phase II, the second phase
will involve the development and initial demonstration of ABU
system features and functions needed to satisfy ground and
aircraft installation options.

Phase II of the project will include:

Trade studies to identify alternatives for the design of
candidate ABU system.

A search for developed, off-the-shelf technology and
equipment to apply to ABU system designs.

The development and demonstration of a laboratory/desktop
model of an ABU.

Development of design specifications and preparation of cost
and time schedules for fabrication of a candidate
"proof-of-concept" ABU system for installation on a navaid
facility for operational evaluation.

3.0 PROJECT SCOPE AND TASKS

3.1 Scope of the Project

To evaluate the viability of developing and implementing an ABU
system, a number of investigative and assessment tasks must be
accomplished. The scope of these tasks includes an examination
of all commonly-used U.S. ground-based navigation and airborne
systems to determine their potential in supporting the required
techniques needed to automate altimeter updates.

For airborne applications, both IFR and VFR operations are
included in a review which considers the range of automated
altimeter update functions or options that appear feasible for
implementation in cockpits, including those involving either
electro-mechanical or electronic displays.

3.2 Project Tasks

The tasks for the evaluation activities (Phase I) include the following:

1. Review ground and airborne procedures (and sources of altimeter setting data) used to update barometric changes to altimeters used in aircraft: operating within the airways structure of the ~~National Airspace System (NAS)~~; and, navigating off-airways.

2. Determine concepts and options that are technically feasible for use in an ~~automated barometric update (ABU)~~ system to provide transmissions of locally-derived altimeter settings from ground-based navigational facilities to aircraft operating within the facilities' area of coverage.

3. Determine requirements for accuracy and reliability appropriate for the design and operation of an ABU system.

4. Investigate technical implications of automatically updating altimeter settings from ground transmitting ABU systems directly to electro-mechanical and electronic altimeter displays in aircraft cockpits.

5. Determine the human factors impact and operational risks associated with implementing the candidate ABU system concepts into the NAS.

6. Prepare a Phase I report, identifying the results of Phase I, Tasks No. 1. through No. 5.

4.0 CURRENT OPERATING PROCEDURES AND NAS SYSTEMS

4.1 Current Procedures

In accordance with FAR §91.81(1) the current procedures for updating barometric flight altimeters involve, for operations below 18,000 ~~feet mean sea level (MSL)~~ (or below the lowest usable Flight Level) setting the altimeter to the current reported altimeter setting of a station along the route and within 100 nautical miles (NM) of the aircraft. When the aircraft is enroute on an instrument flight plan, the ATC controller is required by the FAA Air Traffic Control Handbook (7110.65F) to furnish this information to the crew of an aircraft at least once while the particular aircraft is in the controller's area of jurisdiction. However, for aircraft operating under other than an IFR flight plan, if there is no station within 100 NM of the aircraft, the pilot is required by

FAR 91.81 to set the flight altimeter to the current reported altimeter setting of an appropriate available station. Furthermore, for those flight operations which involve an aircraft not equipped with a communication radio, the altimeter must be set to the elevation of the departure airport or to an appropriate altimeter setting available before departure.

With respect to FAR §91.81 requiring the pilot to set the aircraft altimeter to the setting of a station within 100 miles along his route of flight, Handbook 7110.65F suggests an additional ATC controller procedure. This involves the issuing of a setting of an adjacent station during periods when a steep pressure gradient exists in the area where the aircraft is operating. The purpose of this additional precaution is to inform the pilot of severe differences between the setting being used with the aircraft altimeter and the pressure in adjacent areas. This would enable the pilot to choose a more advantageous setting within the limitations of FAR §91.81.

The established procedures required by FAR §91.81, while addressing the need for appropriate altimeter update information, recognizes that an appropriate source for altimeter settings may not always be available to the pilot operating under VFR flight rules. Therefore, it is conceivable that, for VFR operations, the procedures could allow the use of less appropriate sources for altimeter setting information than would ordinarily be used in IFR operations (e.g., the use of information provided by Unicoms).

General Aviation flight operations are extremely varied in method of navigation, type of weather encountered, altitudes flown, pilot experience, aircraft gross weight, cruising speeds, and capabilities of avionics. Flights may be conducted under instrument or visual flight rules; each has its own regulations concerning current altimeter settings. Enroute altitudes can vary from 100 feet above ground level (AGL) (helicopters) to Flight Level 400.

As identified above, for VFR operations conducted below 18,000 feet MSL, the pilot is required to use the current altimeter setting of a station within 100 NM. If this is not possible, for whatever reason, then the pilot is to use the setting of an appropriate available station. At lower altitudes, terrain may block radio transmissions to and reception from FSS, Flight Watch, and other ATC facilities within 100 NM and even within distances as short as 20 NM from positions along the route of flight. This is particularly a problem in the mountainous and desert areas of the western United States. Distances between airports with fuel, and at most a Unicom operator for communications, are often close to the aircraft maximum range, particularly on westbound flights fighting headwinds. And, with the closing of a large number of FSSs, the availability of

current altimeter settings is reduced even further. Thus, it is quite common for VFR general aviation flights to be conducted using the No Radio (NORDO) procedure of setting field elevation of the departure airport or, per FAR §91.81, an appropriate altimeter setting prior to departure. The next opportunity the pilot has to get a current altimeter setting may well be sitting on the ground after landing at the destination. Or, if the destination happens to be one of the 15% of U.S. airports with a control tower, then the pilot will get the current altimeter setting when within 5 to 30 miles of the airport, depending on radio reception distance. Most Unicoms require that the aircraft be within 1 to 3 miles of the airport, and it is not uncommon to find that the aircraft must be overhead the airport in order to receive Unicom transmissions that are loud enough to be understood.

The effect of altimeter setting errors is to provide erroneous altitude readings to the pilot. For each difference in pressure of 1" of mercury (Hg), the altimeter will show a difference of 1000 feet. 0.1" Hg pressure difference is equivalent to 100 feet of altitude. Over the course of a 300 mile flight with strong pressure gradients, the altimeter setting could change from 30.04 inches of Hg to 29.84 inches of Hg causing the altimeter to read 200 feet higher than actual altitude, i.e. the aircraft is 200 feet lower than the pilot believes it to be. Such a discrepancy has always been a concern for VFR pilots for terrain clearance and compliance with the Hemispheric Rule. The concern is amplified with the increasing demands for tighter vertical spacing controls, particularly for operations near Terminal Control Areas (TCAs), Airport Radar Service Areas (ARSAs), military climb and descent corridors, and other airspace with ~~tight~~ stringent and complex altitude restrictions.

In just those areas where correct altimeter settings are critical for vertical separation of aircraft, the ATC frequencies are often congested. A transiting VFR pilot is reluctant to take up air time to ask for a current altimeter setting. Yet, due to airspace restrictions, that same pilot may not be able to get within range of the Airport Traffic Information Service (ATIS) transmissions, if available, of any controlled fields in the vicinity.

During a typical flight within the NAS, an aircraft will usually operate within the coverage, and most likely along selected radials, of two or more Very High Frequency Omni-Directional Range (VOR)s. The use of VORs for transmitting timely barometric updates to aircraft operating within the areas of the VOR coverage would seem to be a very appropriate option.

4.2 Currently Used Radio Aids to Navigation

Ground-based radio aids to navigation (Navaids) examined in this study for application of an ABU technique include the following

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systems: ~~VHF Omni-Directional Range (VOR)~~, Tactical Air
Navigation (TACAN), Nondirectional Radio Beacon (NDB) and
~~Instrument Landing System (ILS)~~. From the onset of this study it
would appear that the VOR would be the most viable candidate for
modification to add digital or synthesized voice barometric
pressure information to the audio channels because: 1) they are
easily adaptable to this function, and 2) they are the most
widely used navaid within the NAS.

4.2.1 VHF Omni-Directional Range

VORs operate within the 108.0 to 117.95 Mhz frequency band and
have a power output necessary to provide coverage within their
assigned operational service volume.

Figure 1, Typical Ground VOR Transmitter Site

They are subject to line-of-sight restrictions, and the range
varies proportionally to the altitude of the receiving equipment.
VOR stations are classified according to the altitude and
interference-free distance that they serve. The normal service
ranges (distance) for the various classes of VORs are shown in
Table 1.

Within the NAS there are approximately 1,050 VOR systems
installed and classified as Aids to Navigation. Of this number,
approximately 100 VOR systems are also classified as Landing
Aids. Most of the VOR systems are of a design, which would allow
easy modification of an audio subsystems. A lesser number are of
an older design, which, if not otherwise updated, would involve a
more extensive modification, due to the older electronics and
electro-mechanical designs of their code key switches.

Generally, VORs currently provide only station identification, navigation and to/from radial information only. However, there is precedence in using VORs for providing flight crewmembers with communications regarding weather and other high-priority information. This has been done quite routinely in the past through a manually switched communication operation from a controlling ~~Flight Service Station~~ (FSS). In the near future, a limited number of VORs may be selected to transmit, upon activation by a FSS, certain weather data generated by an Automatic Weather Observation System (AWOS). Thus, their value for use in a communication function has been well established.

Table 1, VOR Classes

4.2.2 Tactical Air Navigation (TACAN)

TACAN is a short-range navigation system which supplies continuous, accurate, slant-range distance and bearing information. For military tactical operations, this system provides improved accuracy and greater versatility in beacon installation and mobility as compared to the older VOR system.

Figure 2, DME Sharing TACAN and VOR

VORTAC is the term applied to a radio facility which combines the functions of both VOR and TACAN stations. Bearing information can be received by VOR equipped aircraft while both bearing and range is obtained by TACAN equipped aircraft. VOR equipped aircraft may also obtain range information from the TACAN portion of the VORTAC facility if these aircraft have distance measuring equipment (DME) capable of interrogating the TACAN. Flight procedures for utilizing the VORTAC facility are the same as those used for VOR and TACAN, depending upon which type of airborne equipment is to be used.

The TACAN system has an audio channel for facility identification, similar to the type used on the VOR design. And, like the VOR, it should not be difficult to develop a barometric update capability to operate with this audio feature.

VOR (OR TACAN) System Co-Channel Interference

For two VOR or two TACAN stations to operate interference free on the same frequency, they must be adequately spaced. Insofar as possible, stations operating on the same frequency are separated by a distance that will guard against co-channel interference. However, with the increased installation of these navigational facilities, it may be ~~is~~ possible, at certain locations and altitudes, to receive both stations with approximately equal signal strength. However, even if such interference is encountered, it is most likely to occur only at altitudes above 18,000 feet MSL. Therefore, it should not be a serious consideration for automatic barometric updating concepts applied to VOR or TACAN systems. Above this altitude air traffic would be in the Jet Route System and would have altimeters set to the sea level standard barometric pressure of 29.92 inches of mercury.

Figure 3, Area of Confusion Caused By Co-Channel Interference

4.2.3 Nondirectional Radio Beacon (NDB)

NDBs are used for a number of applications, including the identification of a fix along VOR radials or in conjunction with the ~~Instrument Landing System~~ (ILS) markers. In the latter case they are referred to as compass locators. They are classified as low or medium frequency radio beacons transmitting nondirectional signals allowing the pilot of an aircraft properly equipped to determine the bearing to a selected station and "home" to that station.

The radio beacon comes in three classes:

MH Facility - Power output less than 50 watts (up to about 25 miles of accurate reception under normal atmospheric and terrain conditions).

H Facility - Power output greater than 50 watts but less than 2000 watts. About a 50 mile range, or less in some locations.

HH Facility - Power greater than 2000 watts with a range of about 75 miles.

These facilities normally operate in the frequency band of 190 to 535 Khz. Voice transmissions may be made on radio beacons unless the letter "W" (without voice) is included in the class designator (HW). For identification, radio beacons transmit a continuous three-letter identification in code except during voice transmissions on those radio beacons equipped for voice. Radio beacons are subject to disturbances that may result in erroneous bearing information. These disturbances result from such factors as lightening, precipitation static, etc. And, at night radio beacons are vulnerable to interference from distant stations. Nearly all disturbances which affect the Automatic Direction Finding (ADF) bearing feature also affect the intelligibility of the facility's identification feature.

Radio beacons could be used to transmit barometric updates to aircraft. But, because of disturbances identified above, and the reduced role for nondirectional radio beacons in the NAS, these systems are not considered good candidates with which to provide automatic altimeter updating features.

4.2.4 Instrument Landing System (ILS)

The ILS is designed to provide an approach path for precise alignment and descent of an aircraft on final approach to a

runway. The ground equipment includes, among other things, two
highly directional transmitting systems, a localizer transmitter
and a glideslope transmitter. The localizer transmitter operates
on one of 40 ILS channels within the frequency range of 108.10 to
111.95 Mhz. Signals from the localizer transmitter provide the
pilot with course guidance to the runway centerline. In a
similar fashion, signals from the glideslope transmitter provide
vertical guidance for an aircraft to descend to the proper
touchdown point on the approach end of the runway.

Figure 4, Typical ILS Installation Configuration Reference

The localizer transmitter provides the ILS system identification
through use of International Morse Code, consisting of a
three-letter identifier preceded by the letter I (..*)
transmitted on the localizer frequency. Some localizer

transmitters already have voice transmission capability: those conforming to the earliest (vacuum tube) system design and those conforming to the very newest (digital) system designs. (Note: The design of the ILS localizer transmitters currently under procurement by the FAA as well as those being developed for use in "Non-Federal" installations include such an auxiliary voice communication feature.)

The ILS is a good candidate for inclusion of voice as the means of transmitting both audio identification and high priority information. As discussed later in this report, transmitting high priority voice information--including the latest barometric pressure setting--from the localizer system may be beneficial to pilots of landing aircraft to reduce the need for and reliance on voice updates from the air traffic/tower controller. This application may have an even more important role at uncontrolled airports where no live controller information updates are provided and the flight crews experience increased workload as a result.

The source of the altimeter setting for broadcast on the ILS localizer would be the barometric pressure setting for the airport, as opposed to the concept envisioned for VORs, which would have the barometric pressure sensors located at the transmitter site.

4.3 Current Airborne Systems

4.3.1 Barometric Altimeter

The barometric altimeter is an aneroid barometer calibrated in feet instead of inches of mercury. It's job is to measure the static pressure (or ambient pressure as it is sometimes called) and register this fact in terms of feet or thousands of feet.

The altimeter has an opening that allows static (outside) pressure to enter the otherwise sealed case. A series of sealed diaphragms or "aneroid wafers" within the case are mechanically linked to the three indicating hands. Since the wafers are sealed, they retain a constant internal "pressure" and expand or contract in response to the changing atmospheric pressure surrounding them in the case. As the aircraft climbs, the atmospheric pressure decreases and the sealed wafers expand; this is duly noted by the indicating hands as an increase in altitude. The reverse is true for a descent.

Standard sea level pressure is 29.92 inches of mercury and the operations of the altimeter are based on this fact. Any change in local pressure must be corrected by the pilot. This is done by using the setting knob to set the proper barometric pressure (corrected to sea level) in the Kollsman window.

Most of the altimeters used today also provide encoded altitude
information to the air traffic controller in the form of a code
train linked through the airborne radar ~~beacon or SSR~~ transponder
to the ground based interrogator for display on the controllers
radar. This encoded altitude information is accurate to ~~plus or
minus~~ ± 50 ft. and is used by the controller to aid in
maintaining vertical separation of aircraft within his or her
area of responsibility.

This altitude information is available to the controller on a
continuous basis and does not require the use of voice
transmissions or active pilot/controller input. Transfer of this
information does not utilize frequencies reserved for voice
transmissions. However, the Controller normally only uses this
information as verification of the operating altitude of the
particular aircraft per flight plan clearance and as relayed by
the pilot over voice channels. Additionally, these altitude
encoding altimeters are required equipment on-board any aircraft
operating within the TCA.

Figure 5, Typical Aneroid Altimeter

4.3.2 Flight Management Systems

The cockpit equipment on many modern turbojet airplanes includes
a flight management system (FMS) that performs numerous automated
flight functions. Among their automation features are
capabilities to provide 3-dimensional flight guidance (and

control) over established NAS route structures or even complex, customized navigation profiles. Thus, automated aircraft guidance and control can be accomplished to conform with established airways routing or selected off-airways structures.

Computation of the aircraft position by the FMS is generally based on a pre-programmed flight plan which schedules the FMS to automatically tune selected VOR facilities to provide azimuthal guidance and updates to an inertial reference system to maintain conformance with the selected flight plan. Vertical guidance is provided from the aircraft's barometric sensors and the inertial reference system. If ground navigation aids could be modified to transmit their identification in the form of ASCII code, the FMS could automatically identify and verify the selection of the particular facility. This could provide a backup for the pilot's identification of the selected navaid and serve as another safety feature to reduce the probability of selecting the wrong navigation facility.

4.3.3 Electronic Displays

Another trend in modern aircraft cockpit design is the use of electronic displays for presenting flight and system status information to the flightcrew. The flexibility and reliability of these devices provide sufficient economic incentives to assure their use in cockpits well into the foreseeable future.

These display systems, whether installed in a conventional instrument panel arrangements or incorporated as component of a head-up display system, have the capability to display integrated information formats to the pilot. As such, these devices can provide the pilot with enhanced levels of situation awareness through alpha-numeric and/or graphic display techniques. They could display information on current altimeter settings and--for a navaid identification feature such as the one identified for possible application on the FMS above--provide visual verification of automatic navaid identification.

5.0 ABU CONCEPTS AND SYSTEM OPTIONS

5.1 ABU Concepts

There have been many notable technological advances and developments in the areas of communications and data link transmission techniques since the establishment of altimeter setting procedures many years ago. From these developments it is reasonable to conclude that systems can be developed and procedures can be updated to assist controllers and pilots in reducing workloads; and, at the same time, improve the quality of vertical separation within their areas of responsibility.

The VHF omnirange (VOR) system design, which is in extensive
domestic and international use, includes capabilities which
permit the transmission of auxiliary data such as that which
could be applied to the broadcasting of altimeter setting
information to aircraft operating within its volumetric coverage.
This system offers substantial potential in supporting an
altimeter update communication function. Furthermore,
considering the advances in communication technology, other types
of ground-based navigational aids, such as NDB and ILS, can also
be made capable of providing similar communications support to
pilots operating within the facilities' coverage area. These
various systems could be included with the VOR as candidate
systems to be modified to support the timely updating of
barometric altimeters in all aircraft operating below 18,000 ft.
MSL.

Furthermore, with technology currently available, there is an
opportunity to use digital voice to not only transmit the
barometric altimeter setting but also the facility identifier to
the pilot from the various sources. The two types of
information, identifier and altimeter setting, could be pared
together for rapid information transfer to the pilot--thereby
reducing pilot workloads.

Initially, a pilot flying a VOR tunes to the frequency indicated
in his charts for a particular VOR, listens to the Morse code
identifier to verify selection of the proper VOR. However, since
some pilots don't memorize or maintain proficiency in
transcribing Morse code, the pilot may need to recheck the
appropriate Radio Aids to Navigation and Communication Data Boxes
on the chart to verify the code being received on the VOR audio
channel confirms selection of the proper VOR. This procedure is
proper if the pilot's proficiency in transcribing Morse code is
unreliable.

Without improved pilot skills in the use of Morse code, voice
identification on the audio channel of all aids to navigation--
in particular the VORs--provides a more efficient method of
identification since it involves only one human sensor channel:
the audio channel. The required use by the pilot of both audio
and visual channels to verify a navigation facility presents a
loss of the pilot's time and attention. This resource that might
otherwise be devoted to traffic scanning or other high priority
piloting functions.

An updated operational scenario would allow the pilot to tune the
VOR frequency, listen to the audio channel and verify selection
of the proper VOR rapidly while attending to other flight
functions. Instead of the Morse code, the pilot would receive
voice identification of the name and/or the three-letter
identification of the particular VOR, permitting the pilot to

instantly verify selection of the proper VOR without having to refer back to charts a second time.

In addition, the pilot could also receive a voice altimeter setting update originating from a sensor co-located with the VOR transmitter. The sensor would be a properly calibrated barometric device interfaced directly to the VOR transmitting actual barometer settings for that VOR location on the same audio channel as the voice identifier. For example the pilot could hear "Tupelo VOR, altimeter 29.30". Another station might report "Muscle Shoals VORTAC, altimeter 29.32" The pilot would then set the altimeter to the transmitted altimeter setting of the VOR being used for navigation or one designated as a mandatory reporting point.

The major advantages of this approach would be the assurance that all aircraft flying within the facility's volumetric coverage, could be operating with a common altimeter correction--a setting received when they tuned the particular VOR. As aircraft fly from one VOR coverage area to another and the pilot tunes in a new VOR, a current altimeter setting would automatically be transmitted on the audio channel of the newly selected VOR.

Because this function is automated, it provides several benefits to the pilot and flight service or air traffic control personnel. This benefit is in the form of a decreased workload.

- For the pilot, use of voice, as opposed to Morse code, provides rapid identification of the station selected, eliminating the need for pilots with limited code recognition to refer back to the charts to verify proper station selection. For the VFR operations it would reduce the need to call flight service or other ATC facilities to request altimeter update information.

- For the controller, a reduction of both the frequency and duration of voice communications with the pilots frees up time for other high priority tasks.

- For those aircraft which have been enroute at altitudes above 18,000 ft. MSL and are cleared to descend to a lower altitude for an approach and landing, the controller would know that the pilot would receive current barometric pressure information from the radio aids to navigation which provide guidance upon which the clearance is based. There could be as many as three or four sources of altimeter setting during the descent, approach and landing phase of flight. These sources would be the VORs, ATIS and, if altimeter update information were also provided on the ILS, from the localizer transmitter on final to landing.

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This information could be made available to the pilot during the portion of flight when the cockpit workload is not as critical as that during entry and maneuvering within a TCA or airport traffic area. In addition to the altimeter setting, a digitized facility identifier could provide further reduction of cockpit workload.

5.2 Direct Updating of the Altimeter

Direct updating of the altimeter, as used in this report, refers to an automatic technique whereby the altimeter setting is directly linked or ported to the altimeter. This fully automatic function would not require pilot intervention to set the altimeter. While this technique could reduce the cockpit workload even further, it has negative human factor implications by removing the pilot from the sequence of functions required for setting or changing altimeter settings. By having the altimeter directly updated by the ground navigational facility the cockpit task of updating the altimeter is eliminated; however, it also eliminates the pilot from an important information loop. This could cause problems for the pilot in that, the pilot needs to know if any signal input changes any point of reference. While this problem could be solved by adding an audio or visual indications that the barometric pressure setting for the altimeter is being or has been updated, its impact on implementation and pilot operation should be carefully evaluated.

Benefits associated with directly updating the altimeter setting from the ground include:

- Elimination of this task in the cockpit.

- Eliminating the task from the controller's responsibility.

- No voice transmissions necessary for this function.

- All aircraft operating in the coverage of a specific navaid are all operating with the same barometric reference.

- More efficient use of the existing radio spectrum.

Disadvantages associated with directly updating the aircraft altimeter setting from the ground include:

- Removal of the pilot from the information loop.

- The need for equipment modifications or additional equipment in the aircraft.

- The lack of control as to which ground navaid is used as the update source.

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- The need to inform the pilot that his altitude reference has changed.

- The lack of control as to when and how often the altimeter is updated.

Technology exists which would allow aircraft altimeters to be directly updated; however, this application is not considered as desirable as using digital voice on the audio channel of the navaid. The necessity to provide additional equipment or upgraded equipment in the aircraft could also be a barrier to broad acceptance and implementation. Even though considered not as desirable as digital voice in the near term, direct updating of the altimeter is a technically feasible option. However, as indicated above, this technique could be considered for electronic display applications or use with flight management systems.

At some future time the techniques of accomplishing direct updating of altimeters may find application in displaying on electronic displays the altimeter setting as well as the identifier of the navigational aid from which the altimeter update is transmitted. This may also have specific application with off-airways navigation through use of flight management systems where multiple navigational aids may be used for determining not only the aircraft position but also an appropriate altimeter setting for that position.

For off-airways navigation using a flight management system, digital data could be made available from an ABU concept to provide alpha-numeric identification of selected VOR facility, and, using on-board systems, automatically validate the VOR selections. From the altimeter update data (for flights below 18,000 MSL) on-board systems could calculate altimeter settings for the position over which the aircraft is operating.

These applications would require an established time frame within the transmitted VOR message to transmit the necessary data (ASCII code). Using this arrangement, the digital voice message transmission would include data for the VOR identification and altimeter setting calculation. Such a concept is considered to be technically feasible.

5.3 Digital/Synthesized Voice

The method used by an Automatic Barometric Update system to convey the altimeter setting to the pilot is critical to the ABU system's easy and accurate use by the pilot. The preferred approach would be spoken annunciation by an automatic computer speech generation system.

Pilots now receive altimeter settings in the speech mode while
leaving their eyes unencumbered for more time-critical flight
tasks and for traffic watch. Speech annunciation requires no
additional panel space and no purchase of additional hardware by
the aircraft owner. Provided the pilot can choose when to listen
to a spoken message, as would be the case with the ABU broadcast,
the chances of mutual interference among the spoken altimeter
setting and other cockpit voice communications are greatly
reduced.

An investigation was conducted to determine the computer speech
technology options, including both digitized and synthesized
speech, which are technically feasible and also sound from a
human factors perspective.

Of particular importance is speech intelligibility in the
cockpit environment, using the particular audio transmission
characteristics of the navigational aid broadcast channels.

This study addresses, first, the performance of speech
annunciation technology in the cockpit, and second, general
approaches to the design of speech system hardware and software
that will provide the flexibility needed for an initial
barometric update system that will facilitate system improvements
and upgrades over time.

6.0 SPEECH TECHNOLOGY PERFORMANCE IN THE COCKPIT

6.1 Methods of Computer Speech Generation

There are two general approaches to generating speech and
composing spoken messages via computer. These are "synthesis by
rule" and "synthesis by analysis." Other terms for
synthesis-by-rule are "synthesis," or "true synthesis." Other
terms for synthesis-by-analysis are "digitized speech" and
"compressed speech."

In the synthesis-by-rule approach, speech is generated entirely
by rules or algorithm without use of any human recordings. The
output of the algorithm is a set of data which can be converted
to an audio waveform that is perceived as speech by human
listeners. We use the term "synthesized speech" in this report
for speech generated by this approach.

In the synthesis-by-analysis approach, speech is generated by
reconstructing previously recorded segments of human speech.
These pre-recorded segments, usually words and phrases, have been
digitized, and perhaps compressed, then un-compressed, and output
via digital-to-analog conversion. We use the term "digitized
speech" for speech generated by this approach. Within each of
these two approaches there are a variety of methods employed.

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Synthesized speech may be generated from normally spelled text strings, from a phonemic (speech sound) string, from sub-phonemic strings (called allophones) or from an array of computed variables corresponding to acoustic parameters of speech or articulatory parameters of speech pronunciation. Synthesizers that take text, phoneme strings, or allophones as input rely on speech generation algorithms that compute acoustic or articulatory parameters.

Synthesized speech systems have an unlimited vocabulary. Message storage, as text or phoneme strings, is very economical for the text-to-speech and phoneme synthesizers, about 96 to 112 bits (12 to 14 8-bit bytes) per second of generated speech, assuming a speaking rate of 150 words per minute. Voice quality of speech synthesizers can be male, female, or child. All synthesized speech sounds mechanical to some degree.

The software that generates the speech must handle not only the generation of the correct speech sounds. It must also adjust the pitch, duration, and amplitude of individual syllables within the words, depending on the position of the words in the message. Without proper adjustment of pitch and rhythm, technically "speech prosodics," the message is hard to follow and may be misunderstood or, if understood, not easily remembered. (See Simpson, 1983 for further detail.)

Digitized speech systems have limited vocabularies; the vocabulary is limited to the words and phrases that have been recorded by a human speaker, digitized, and stored. The storage requirements vary greatly with the digitizing parameters and compression algorithms used. (See Figure 6 for a comparison of vocabulary storage requirements of synthesized and digitized speech generation techniques.)

Digitized speech may be simply digitized at a relatively high sampling rate and reconverted to analog. Compact Disk and Digital Analog Tape Players represent the high end of this process. Good quality speech with easy identification of the original speaker can be obtained at sample rates of 20 Khz with 8 bits of amplitude for 160K bits (20K bytes) per second of stored speech. Using various compression algorithms, one can reduce the storage requirements. Adaptive predictive coding (APC) can result in 9600 bits (1200 bytes) per second of stored speech (e.g., the U.S. Government APC-4 algorithm). With linear predictive coding (LPC) the storage can be even further reduced. The Government's LPC-10 algorithm requires 2400 bits (300 bytes) per second. At the extreme low end, the Texas Instruments Speak-N-Spell toy used an LPC algorithm that required 1200 bits (150 bytes) per second to store its speech--a vocabulary of words, phrases, and names of letters. Speech naturalness decreases with the lower storage rates. At the 2400 bit rate the speech sounds slightly mechanical. At the 1200 bit rate, it is definitely mechanical.

When digitized words and phrases are concatenated to compose
messages, different versions are needed of any word that can
appear in different message positions. The concatenation
algorithm must use the correct word version. Otherwise the
prosodics will be wrong and this will lead to misunderstanding
and difficulty in remembering the message.

Figure 6, Comparison of Vocabulary Storage Requirements

6.2 Speech Intelligibility and Comprehensibility

Both synthesized and digitized speech are highly intelligible in
cockpit noise, even in negative signal-to-noise ratios, provided
that the speech has been properly generated at the phonetic and
prosodic for speech annunciation systems. Speech synthesizers
operate in the range of 80 to 250 words per minute. Digitized
speech, encoded as whole phrases, will depend on the speaking
rate of the original human speaker and will vary from 50 to 300
words per minute. When individual stored words are concatenated,
the maximum rate drops to about 1 sec per word or 60 words per
minute, mainly because humans speak much more slowly when saying

individual words. Editing of the digitized speech data can speed up the rate to around 80 to 100 words per minute. For computer generated spoken warning messages in the cockpit a speaking rate of approximately 150 words per minute is recommended.

6.3 Voice Quality

Both male and female sounding speech is available from some speech synthesizers; others are limited to male speech only. All models have some range of programmable pitch and speech rate. Some models permit manipulation of the voice quality. For digitized speech, voice quality is determined by the voice of the original human speaker.

In the case of compressed speech, e.g., APC or LPC, the clarity and intelligibility of the speech is heavily dependent on the voice characteristics of the individual speaker. Lower pitched voices usually work better, and a good female voice is difficult to find. Vendors of digitized speech vocabularies guard their speakers as proprietary resources. Voice quality from one recording session to another also varies greatly for most speakers. Those few speakers who can match the quality of earlier recording sessions are also highly valued since vocabulary expansion for digitized speech systems depends on the ability to obtain new recordings from the same speaker.

The choice between natural sounding and mechanical sounding speech depends on the application. For systems that are simulating a human, e.g., ATC training systems, natural-sounding speech is preferred. For systems that are providing spoken output from a machine, e.g., a cockpit voice warning system, machine-sounding speech is preferred (Simpson, et al, 1987). Studies of pilot preferences for voice quality have consistently shown that pilots prefer a distinctive sounding voice for cockpit speech annunciation systems. Before the advent of computer-generated speech, and when human female voices were rarely heard in the cockpit, a female voice was preferred over a male voice (Brown, Bertone, and Obermeyer, 1968). Today, the preference is for a slightly mechanical sounding voice (cf, SAE ARP-4153, 1988).

6.4 Message Development

The cost of developing messages for a particular application differs for synthesized and digitized speech in the type of expertise required, the development process, and therefore in the time required. The simplest development is for a good text-to-speech synthesizer. Messages consist of text strings for each word or phrase in the vocabulary. New words and phrases are added by adding text strings. Current text-to-speech systems vary in the accuracy of their spelling-to-sound rules and their prosodics. Some creative misspellings are usually needed for

such non-standard, and therefore difficult, words such as
"pilot", "altimeter", and "fuel." The numbers and the letters of
the alphabet are usually correctly pronounced, although the
phonetic alphabet is not necessarily correctly pronounced. For
phoneme synthesizers, an expert in phonetics is needed to program
the phoneme strings. Actual programming time is equivalent, for
a phonetician, to normally spelled text string programming for a
non-phonetician.

For digitized speech, any reasonably experienced audio technician
can record high quality speech. However, the speech phrases and
words must then be edited by a phonetician to ensure the proper
prosodics when they are concatenated into messages. For
compressed speech using an LPC algorithm, or compressed spectral
data, extensive editing of the pitch data and the LPC
coefficients or spectral parameters by a phonetician experienced
in speech editing is required to produce intelligible speech. If
additional words are added to the vocabulary, the original
speaker and the original recording apparatus must be used. The
speaker must adapt his or her pronunciation and voice quality to
match that of the original recordings.

6.5 Speech System Design

The design of the speech generation system for ABU can be
tailored to just that specific application or can be made with
provision for expansion of functions. We call these
"ABU-specific" and "general purpose" designs.

For the ABU-specific design, the components needed are:

- speech generation device,

- stored vocabulary,

- data-to-message conversion routine,

- vocabulary retrieval and concatenation routine,

- speech device handler routine,

- host system consisting of a CPU and memory to run
  the software.

For a general purpose design (non-ABU-specific), a message
composer module would be needed. This module would receive input
from other sensors or possibly by data link from ATC computers
and would compose messages using message syntax capable of
handling ATC phraseology for a number of different types of
information such as winds aloft, ATIS data, and any other useful
weather or navigation information. The output from this module
would be the input to the data message conversion routine.

For the "brassboard-quality" ABU system, a general purpose CPU is required for flexibility. An IBM-PC XT or AT compatible will be adequate, is relatively inexpensive, and is available off the shelf. For a "certifiable quality" system (production version) custom circuit boards must be designed to meet the reliability and environmental standards required for such a system.

Speech Generation Device

The hardware for an ABU-specific design would consist of a synthesizer or digitized speech device, non-volatile memory for vocabulary storage and software, a port or a buss for communication with the speech device, and analog audio output hardware for proper audio signal filtering and amplification prior to input to the ABU transmitter. The synthesizer or the digitized speech device could be board level; several are available. Synthesizer chips and digitized speech playback chips are also available. These require power supplies, some working memory, buffered input, and handshaking.

In quantity of one, speech synthesizer boards and some development software to support them in the MS-DOS IBM-PC compatible environment are available for around $400.

A number of speech digitizing and playback boards are also available. Most of them have been developed for voice mail applications and do not provide for any editing of the messages. Some provide editors for editing the spectral parameters or the LPC coefficients, an essential requirement for ABU vocabulary development for a digitized speech system. Prices of the cheaper of these in quantity of 1,000 are about $700.

Stored Vocabulary

The non-volatile memory needed for vocabulary storage depends on the speech generation approach used. An estimate was made for synthesized and for digitized speech using various DEV AIR Technical Associates speech development laboratory systems. At a minimum, the ten digits and the word "altimeter" would be required for ABU readouts. Station identifiers, if desired, for the 1,050 VOR's in the U.S. would add that many words to the vocabulary. The word "VOR" would then also be required.

DEV AIR Tech has developed a digitized, LPC-encoded vocabulary, which includes the ten digits, with the three position variants needed for correct prosodics. This vocabulary was developed for the Texas Instruments TMS-5220 speech chip using an in-house speech editor. The 30 vocabulary items for the 3 versions of the 10 digits requires 3,004 (0BBC H) bytes. "Altimeter" would need another 200 (0C8 H) bytes. Since VOR names are polysyllabic, with one to three words, they take relatively more memory.

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Assuming 2.8 syllables per name, estimated from a list of VOR names, 1,050 names, plus the word "VOR" would require another 147,000 (222E0 H) bytes.

DEV AIR Tech has a Sonix Speech synthesis development system, using the SSI-261 (SC-02) speech synthesizer chip, on a board for the IBM-PC. The codes for the ten digits require 60 bytes to store the phoneme codes, plus a pitch and duration adjustment algorithm to generate the three pronunciations for initial, mid, and final position. The phoneme codes for "altimeter" would take about 10 bytes. The phoneme codes for the 1,050 VOR names would take about 15,800 (3DB8 H) bytes. However, the necessity to store words and numbers for all 1,050 VOR's and VOR names would not be necessary if the synthesize speech program were programmed specifically for each location. This would significantly reduce the storage requirements for all approaches of speech synthesis.

DEV AIR Tech also has a sound-spelling algorithm for the Votrax PSS synthesizer, which uses the SC-01 synthesizer chip. This sound-spelling algorithm pronounces the digits directly from the ASCII characters. Therefore no storage is needed for the digit vocabulary. The algorithm, written in C, resides in 8.4K of memory. It will also pronounce any sound-spelled string such as the name of a VOR. For example, the sound-spelling for the Central City VOR would be "sentru-l sity", for Chico, "cheekoe-". Sound-spelling requires about 20% more characters than normal spelling. Its advantage over text-to-speech is that the phonetic and prosodic accuracy of the speech can be assured with sound-spelling. This is particularly critical for place names.

As can be seen in Table 2, synthesized speech requires about one tenth the vocabulary storage as digitized speech of the lowest acceptable quality. For very small vocabularies and small, fixed message wording, this difference is negligible. As vocabulary size and message variations increase, the difference is real in terms of memory requirements and associated components.

Data to Message Conversion

The data to message conversion routine takes sensor-supplied data, e.g., the current altimeter setting, and converts this to the correct sequence of words for the ABU message regarding current altimeter setting.

Vocabulary Retrieval and Concatenation

The vocabulary retrieval and concatenation routine takes the output of the data to message conversion routine and gets vocabulary, with the proper timing for correct prosodics, cued up to be sent to the speech output device. This routine has some simple prosodics rules to ensure that syntactic pauses are inserted at the right places. For a synthesized speech system,

it would concatenate the addresses of the stored codes (text or phoneme) for the word "altimeter", followed by the four digits of altimeter setting. It would encode the digit words for duration and pitch according to their position in the message. In a digitized speech system, this routine would concatenate the addresses for the stored data for "altimeter" followed by the addresses for the correct versions of each of the digit words.

Table 2, Synthesized vs. Digitized Speech Memory Requirements

	Basic Vocab Digits + Altimeter	Extended Vocab 1050 VOR names + VOR	Total Vocab
Synthesized Text-to-Speech	9	8840	8849 bytes
Synthesized Sound-spelling	10	11050	11060 bytes
Synthesized Phoneme Strings	70	15800	15870 bytes
Digitized LPC-encoded 2400 bits/sec	3204	147000	150204 bytes

Speech Device Handler Routine

The speech device handler routine communicates with the speech device and sends it data at the proper time.

Host System

The host system will consist of a general purpose CPU, memory for program and data storage, and associated support circuitry such as power supplies, and external interfaces.

Message Composer

In the general purpose design, a message composer module puts messages together at a higher linguistic level than the data-to-message conversion routine, using a variety of sensor inputs and other relevant information as appropriate. The data to message conversion routine knows how to compose one type of message, e.g., an altimeter setting. The message composer knows the correct phraseology for a number of types of messages, e.g winds aloft, current surface weather, wind shear alerts. If its

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design is linguistically sound, it will handle new message types that were not originally envisioned.

The case with which the pilot can process altimeter setting information provided by an Automatic Barometric Update System while performing normal or emergency flight tasks is important to the success of the ABU. Since the annunciation of altimeter setting will be via computer generated speech, a number of human factors issues regarding human audio information processing must be considered.

Furthermore, the ABU system must work well for pilots operating under the entire range of categories of flight operations that are subsumed under general aviation and air transport operations.

6.6 Human Processing of Spoken Information

Speech is an extremely robust code for information transmission to humans. We have evolved it for our use over tens of millennia, and it can withstand very poor, even negative signal-to-noise ratios, i.e. humans can understand spoken messages that are softer than the surrounding ambient noise. We can also pick out and follow a particular voice and the message it is transmitting in a background of other speech. Individuals differ in their ability to do this, but nearly everyone can follow a particular conversation out of several in progress at a party, a phenomenon called the "cocktail party effect." The cocktail party effect is made possible in large part by the high level of redundancy in conversational speech and the linguistic context provided by the complete or nearly complete sentences that are spoken. Pilots develop this ability to some extent for ATC communications. However, because ATC phraseology has been purposely made more concise, to save time on the air, there is less redundancy of wording to help the pilot. The standard phraseology does provide some linguistic context, but nearly every word is critical to the meaning of the transmission. A word missed, particularly a digit, may not be retrievable from context. Worse, a digit misunderstood can result in wrong headings, altitudes, and altimeter settings, to list a few.

The ABU spoken messages will have to be tested for intelligibility, not only in backgrounds of typical aircraft cockpit noise at representative signal reception levels, but also mixed with representative ATC communications. Additionally, tests will be required of pilot ability to remember an ABU-delivered altimeter setting and also to correctly understand simultaneously spoken ATC clearances.

6.7 Criteria for Selection of Speech Generation Technology

We have studied both digitized speech and synthesized speech for the ABU application and compared them for eight criteria, listed below, to guide our selection of technology for the ABU speech annunciation system.

- Intelligibility in cockpit noise,

- Intelligibility in competing cockpit speech,

- Intelligibility if transmitted via the 10% modulation channel of VOR's,

- Ease of upgrade to add speech messages to the system,

- Discriminability of ABU voice from other cockpit speech,

- Amount of program code needed to implement speech annunciation,

- Hardware required to implement speech annunciation,

- Upward compatibility with future technology.

Intelligibility in Cockpit Noise

Speech is extremely robust with respect to its intelligibility in noise. The digits are particularly easy to recognize. A study of the intelligibility of human speech mixed with different levels of background noise showed the digits to be nearly 100% intelligible in a signal-to-noise ratio of -6 dB. That is, the noise was 6 dB louder than the speech. (Miller, et al, 1951). Figure 7, taken from that study, illustrates this.

Similar results can be obtained for the digits spoken by computer generated speech. Provided the speech vocabulary is properly developed, and the speech is well-coded phonetically there is no particular advantage of digitized or synthesized speech. Both will be highly intelligible in cockpit noise at signal-to-noise ratios of 0 Db or higher, i.e. when the peak level of the speech in dB is equal to or greater than the average level of the noise in dB.

Intelligibility in Competing Cockpit Speech

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To the extent that synthesized speech is more mechanical sounding than digitized speech, the synthesized speech is predicted to be more intelligible in competing cockpit speech because of its distinctiveness. This distinctiveness will permit the pilot to more easily track that voice, and this will indirectly improve intelligibility.

Figure 7, Intelligibility Scores for Different types of Spoken Material as a Function of Signal-to-Noise Ratio

Intelligibility if transmitted via the 10% modulation channel of VORs

A VHF Omnirange station produces a signal that can be decomposed by a receiver into two distinct outputs. The signal is 30% modulated by a 30 Hz rotating beam signal and 30 % modulated by a 9600 Hz subcarrier which is in turn FM modulated by a 30 Hz reference frequency. Both these are demodulated and filtered in the aircraft receiver to produce the voltages which drive the

course deviation indicator, and do not interfere with additional modulation of the VOR signal for purposes of voice identification or communications. (Bose, 1970)

A test was performed with a portable aircraft radio receiving the San Jose, CA VOR on frequency 114.1. The background audio system noise and the Morse identifier were recorded on audio tape and the signal-to-noise ratio obtained via portable storage oscilloscope. The signal-to-noise ratio of the Morse code station identifier against the background of the noise as received by the radio was conservatively measured as +1.5 dB. This is above the minimum of 0 dB S/N needed for good intelligibility of altimeter settings via synthesized or digitized speech. It would not be an adequate signal-to-noise ratio for a voice warning. But it is adequate for voice messages that are expected and that the pilot is listening for. A somewhat better signal (about 8 dB signal-to-noise) was recorded using an aircraft receiver and the Salinas, California VOR (Figure 8). Further tests will be needed in Phase II with varying distances from the station and with representative samples of altimeter readouts. However, the results of initial test are reassuring.

Figure 8, Signal Recorded From Salinas VOR Signal to Noise Ratio

Ease of Upgrade to Add Speech Messages to System

It is much easier to add speech messages to a synthesized speech system than to a digitized speech system. For a synthesized speech system, the text, sound-spellings, or phoneme codes, as appropriate, must be developed. These can be done by anyone with expertise in phonetics. For digitized speech, the original speaker must be employed using the same audio system and environment for recording. Then the speech data must be edited by an expert in phonetics who is also familiar with the spectral features or LPC algorithm used for compression for that particular digitized speech system.

Discriminability of ABU Voice From Other Cockpit Speech

Synthesized speech is more distrainable from human voice speech in the cockpit than is digitized speech. Digitized speech can be edited to make it more mechanical sounding and thus more discriminable.

Amount of Program Code Needed to Implement Speech Annunciation

Assuming that the vocabulary for a digitized speech system includes variants of pronunciation for those words that appear in more than one position, then the program code needed to look up the addresses of stored words and phrases and send the associated data to the speech output device is small. Handshaking complexity and transfer buffer handling vary somewhat depending on the device. Similarly, the code needed to look up phoneme strings or text strings and send them to a phoneme synthesizer or a text-to-speech synthesizer, respectively, is equally small. If a text-to-speech algorithm is not included in the synthesizer itself, then the code needed to perform the text-to-speech conversion, including the rules, may take 32K to 64K, depending on the quality of the rules. The code for sound-spelling takes less room, around 8 to 10K, and actually provides better pronunciation and prosodics than any of the text-to-speech algorithms, provided the sound-spelling strings are edited by a competent phonetician.

Hardware Required to Implement Speech Annunciation

While chip level components are available for both digitized and synthesized speech output, both approaches require additional support chips, memory, and audio filtering and amplification. Thus a broad level component, whether designed in-house or purchased, is required. A dedicated processor is needed for any sound-spelling or text-to-speech algorithm. Vocabulary storage memory requirements for the two approaches are on the order of 1 to 10 for synthesized versus digitized speech.

Upward Compatibility With Future Technology

A system based on a phoneme or text-to-speech synthesizer will be far easier to upgrade to accommodate new technology than a digitized speech system. This is because the stored vocabulary data remains the same for text-to-speech synthesizers and very nearly the same for phoneme synthesizers. In contrast, the input data for a new digitized speech algorithm is likely to be completely different, necessitating the total replacement of all existing vocabulary codes and the re-digitizing, compressing, and editing of the old vocabulary along with any new vocabulary.

7.0 IMPLICATIONS Of ABU

7.1 Impact of ABU on General Aviation Operations

Nearly all aircraft have the capability to receive VOR transmissions. Indeed, many of the inexpensive handheld aircraft transceivers which are now being sold as "backup" units for IFR flight and primary units for aircraft without electrical systems receive VOR stations. Many of these units are used in aircraft which up to now had no two-way radio capability such as sailplanes. Even if the VOR stations are not used for navigation, for example if the aircraft used Loran as its primary navigation system, the capability to receive VOR stations is usually available. Thus, if an altimeter setting could be obtained without using the limited battery power of a handheld to transmit a request to a ground station, or if a VFR aircraft enroute navigating by Loran could obtain an altimeter setting which would allow him to use his vertical navigation functions more accurately, then this could become a very popular and useful additional service.

A question which needs to be addressed with any additional audio information source in the cockpit is that of auditory workload. In airline operations, the proliferation of audio warnings, horns, and voices from radios and intercoms has become a serious concern. In general aviation, the problem is less because of fewer systems in most of the aircraft. However, with some light twins and more complex pressurized singles, audio workload at a critical time in the flight is a possibility. It is very unlikely that the ABU would contribute in any significant way to this problem, since turning on the ABU is entirely a pilot-initiated action, and even if the VOR audio were left running while another task was attended to, the pilot would have no question about how to shut down the offending audio (turning down a radio volume control or clicking off a switch on the audio panel, a very highly over-learned and well-practiced operation).

7.2 Impact of ABU on Air Carrier Operations

The ABU technique has applications that could be beneficial to air carrier operations. From a human factors perspective, the ABU coupled with voice identification of ground navaid has

potential to improve efficiency of information transfer between the ATC controller and the flight crew. For the flight crew, the techniques could reduce communication workloads as well mental workloads in certain time-critical flight scenarios. And, because the air traffic control system provides the other side of the communications traffic, reduced communication workloads may also benefit the controller.

This is particularly the case for the air traffic control scenarios involving aircraft departing the high altitude Flight Levels, penetrating the low level airways structure to execute an approach and landing at a destination airport.

An example of a typical scenario is as follows: "Delta 234 descend to cross Boile⌐ at or above FL 240, maintain one six thousand, reduce airspe-d to 270 kts. indicated, altimeter 30.12." This is soon followed by "Delta 234 cleared present position (J-89) direct Chicago Heights (CGT) Victor 7 Niles (Fix 18 NM Northwest on the 356 radial CGT), direct O'Hare."

In the receipt and execution of this clearance, having the identification on the VORs and being able to receive the altimeter setting at the time the VOR is identified would provide a significant reduction in cockpit workload. This would be especially beneficial during flight scenarios characterized by heavy communication traffic and limited crew response time. This is becoming the rule rather than the exception in current air carrier operations.

During the transition from the enroute to the approach phase of operation the flight crews mental information workload continues to elevate from the start of the descent profile through the landing rollout. It may be described graphically through depiction of a "time compression" cone (Figure 8) in which the diameter of the cone represents time available for the crew to acquire information, mentally process it, and accomplish required cockpit functions.

Figure 9, Mental Workload "Time Compression" Cone

As the operational requirements elevate, due in part to the time-critical flight maneuver requirements, the mental workload cone compresses, requiring more current and timely information updates. This results in a need for extremely efficient two-way communication procedures and techniques. The use of voice identification of the navigational aids and ABU techniques for setting and/or verifying altimeter updates may satisfy some of these needs.

Other improvements may be found through structuring of vital information in a highly intuitive format and transferring that information through the voice systems envisioned for application to the ABU function. This may permit flight crewmembers to mentally format the essential information for use at the appropriate time. Essential information might include (for VORs that serve as feeder fixes) the minimum enroute altitude (MEA) or minimum sector altitude (MSA) between the fix and the airport. This information could be considered to be static information because it is not affected by dynamic or changing traffic conditions or runway environments. Its revision would not, therefore, be required frequently or on short notice.

Uncontrolled airports generally have four feeder fixes to the approach patterns. As with Savannah, for example, the VOR has no information to alert flight crewmembers for situation and pattern awareness. Information could be transmitted from an ABU equipped VOR to provide basic information to flight crewmembers unfamiliar with the airport and its "uncontrolled" procedures. However, when structuring the basic information for transmission, the assumption should be that crewmembers will be unfamiliar with most of the criteria relating to the flight procedures of the particular airport. Approaches flown to uncontrolled airports by air carrier operators are often the last approach of the night for the particular crewmembers. And, there are enough differences from normal controlled airports that potential for confusion is high. Such factors as: the need to spend time to conduct a search for little used information, normally elevated workloads in the approach and landing phase of flight, and (in the case of operations late in the crew duty cycle) fatigue contribute to mental mistakes on the part of the crew. Additional information from the feeder fix VOR could make these "late-hour" approach and landing operations somewhat safer.

Airports with parallel runways have conditions and situations in which both controller and flight crewmember could benefit from "voice information enhancement" (e.g., ATL, LAX, DFW). During profile entries there is continuous runway switching due to flow

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control requirements. The flight crewmembers must hastily retune ILS receivers and <u>identify</u> frequencies, courses, barometric and radio altimeter settings, and outer marker information for each runway change. During high density arrivals, the VHF communication frequencies are heavily saturated, making it difficult for requests, acknowledgments, confirmations or informational updates. Certain basic voice information placed on the ILS along with the identification and altimeter setting may provide some relief for these very busy air traffic scenarios.

7.3 Accuracy and Reliability Requirements

Airborne Requirements

Since no special airborne systems would be needed for an ABU concept which uses the audio channels of existing navaids to up-link ABU voice transmissions, no new accuracy or reliability requirements would be generated. However, from the human factors point of view, issues identified above relating to intelligibility of an ABU voice in cockpit environments and discriminability of an ABU voice from other cockpit speech must be evaluated. Using these evaluations it is reasonable to conclude that a need to maintain some form of ABU voice system quality will emerge. Currently, there are on-going activities within the Government, industry, and among technical societies to develop measures or criteria for the specification of synthesized or digitized voice.

Ground System Requirements

For the ground side of the system, the proposed concept would provide a modification to the existing VOR and ILS ground systems, in the form of a barometric sensor device and interface circuitry, which would transmit current local barometric pressure information to the pilot on a continuous basis. Standards for accuracy and reliability of barometric sensor devices are well established.

Currently, weather data, including barometric altimeter settings, are being transmitted to the aircraft via voice channels either from the controller upon initial contact by the pilot, from ATIS transmissions at the larger airports, or from automated weather observation systems (AWOS). Sensors used in the weather observation systems that support these services are certified and maintained to established accuracy and reliability standards. Accuracy requirements for ABU sensors, which would be located at the transmitter sights, could be expected to conform to the accuracy criteria used for the current family of ground based barometric sensor equipment employed within the NAS.

For reliability of the ABU system, the operation must be fully automated and operate unattended for time periods consistent with

operations, monitoring methods, and maintenance schedules applicable to the particular navigation facility.

8.0 CONCLUSIONS

As a result of the study of the considered options and an assessment of the potential impact on general aviation and air carrier operations, we have concluded that there are no insurmountable human factors or operational problems associated with the implementation of ABU. However, this conclusion relates only to concepts for the automatic transmission of the barometric through synthesized or digitized voice updates from ground-based radio aids to navigation. Furthermore, we believe there is potential for improvement in aviation safety by implementing ABU techniques. These improvements could be in the form of: 1) enhancement of the quality of altimeter setting data used by VFR flight crewmembers operating below 18,000 feet MSL, 2) a reduction of workload for flight crewmembers operating in either VFR or IFR environments, 3) a reduction of air traffic controller workload and, 4) a small, but positive, reduction of traffic on ATC communication channels.

Issues relating to intelligibility of an ABU voice system in cockpit environments and the discriminability of an ABU voice from other cockpit speech remain to be evaluated. This is needed to establish desired characteristics and quality criteria for developing and customizing "voice" options for implementation in an ABU system.

Furthermore, the type of voice, synthesized or digitized, for use with an ABU system cannot be adequately selected without assessing their suitability in cockpit environments. From preliminary analysis, considering economic and system growth factors, synthesized voice has merit over digitized voice. However, more data on human response to these two "voices" are needed to support selection of an appropriate voice generation concept.

With respect to ground-based navaids to be considered as candidates for use in an ABU application, the VOR and TACAN systems appear to offer the most cost/effective options for implementation. These navaids are used extensively throughout the NAS, voice channels are available to support transmission of ABU information to aircraft operating within their service, and most civil and military aircraft are currently equipped to receive either VOR or TACAN transmissions. Furthermore, modification of airborne equipment would not be required for receiving ABU communications from these navaids.

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Since not all ILS systems are currently configured to provide voice communication, their role in any ABU implementation would not be as attractive as that of the VOR or TACAN system. And, because of interference and reception limitations associated with the NDB system, this navaid is one of the least attractive candidates for and ABU application.

It has also been concluded that the concept of direct updating of altimeters from an ABU system has potential for human factors complications. Its consideration as a concept option would require the addition of cockpit advisory and display capabilities to prevent the pilot from being eliminated from the information loop when ever the altimeter is updated. It is not considered a viable option at this time.

9.0 RECOMMENDATIONS

The recommendations based on this study are:

1. Focus on the use of VOR and TACAN navigation aids as the prime candidates for any further development and planned implementation of an ABU system.

2. Consider the merits of both synthesized and digitized speech as a concept for transmission of both identification and altimeter setting data from the VOR/TACAN navigation aids.

3. Using both synthesized and digitized voice generation techniques, undertake the resolution of issues regarding intelligibility and discriminability of ABU voice in cockpit environments, considering appropriate levels of ambient cockpit noise levels and competing cockpit speech.

4. Select one voice generation technique for implementation in an ABU.

5. Develop a "brassboard" quality ABU system for demonstration and analysis activities.

6. Develop an ABU system design, with appropriate cost data, for the fabrication and installation of a "proof-of-concept" ABU system on a selected VOR facility for an operational evaluation.

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